Agricultural Water Management 203 (2018) 138–150

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

The increasing effects in energy and GHG emission caused by groundwater level declines in North China's main food production plain

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ARTICLE INFO

Keywords:
Energy consumption
GHG emissions
Pumping irrigation
North China Plain

ABSTRACT

Agriculture consumes a huge amount of energy every year and then emits lots of greenhouse gases (GHG). Reduction of agricultural energy consumption is important to sustainable agriculture and mitigation of climate change. Groundwater is the main irrigation source in north China's main food production plains, North China Plain (NCP). Many studies have shown that the groundwater levels here have declined a lot during past decades. However, the related environmental and economic impacts have been rarely researched. This study carries out a detailed research on the changes in energy cost and GHG emissions caused by groundwater level declines on the NCP. Results indicate that during 1996–2013, total agricultural groundwater consumption here has increased by 20%. Over-exploitation of groundwater has caused severe groundwater declines (0.6 m yr^{-1}) and the decline rate has become faster in recent years. As a result, energy use rate for pumping unit water has increased from 0.50 to 0.61 kWh m^{-3}, by nearly 22%. Therefore, GHG emissions have increased from 6.16 to 8.72 Mt CO_2e, by 42%. Hebei suffers the most serious groundwater level declines and emits most GHG from pumping, accounting for 47% of the total emissions in the NCP. The economic cost of energy consumption and emission reduction for pumping irrigation is US$ 1.25 billion in 2013, reaching up to 10.3% of GDP in this region. The increasing cost is a great threat to sustainable development of agriculture. Water-saving irrigation is one of the most effective ways to reduce water and energy consumption without loss of grain output. To reduce GHG emissions and pressures on energy and groundwater resources, water-saving irrigation should be greatly promoted in this region. The study would contribute to the development of water-saving and energy-saving agriculture.

1. Introduction

Climate change caused by increasing energy consumption, and GHG emissions has become a common concern of the international community. The Paris Agreement fully embodies global change as not only significant for the interests and development of each country but to the whole world. In the past six decades, energy-consumption patterns in agriculture have changed enormously (Cleveland, 1995; Leach, 1976). Today the agriculture sector is one of main contributors to energy consumption and GHG emissions (Barker et al., 2009; Devi et al., 2009). Each year, agriculture emits 10–12% of the total estimated GHG emissions ($5.1 - 6.1 \times 10^3$ Mt CO_2e yr^{-1}) (Niggli et al., 2009). Studies of the direct energy use of on-farm operations suggest that groundwater pumping for irrigation is one of the highest energy-consumption processes (Lal, 2004; Mushtaq et al., 2009; Singh et al., 2003).

This issue is especially severe in China because of its agriculture depending largely on the groundwater pumping irrigation. China is the world's largest emitter of GHGs, and its GHG emissions have drawn widespread attention both domestically and internationally. As a signatory to the Paris Agreement, China has committed to reducing GHG emissions per unit of GDP by 2030 to a level that is 60–65% lower than the amount emitted in 2005. The national GHG emissions are estimated to reach a peak in approximately 2030. Meanwhile, as the world's second largest irrigator, GHG emissions from agriculture are responsible for 17–20% of the nation's total annual emissions (Wang et al., 2010), which is almost doubled from the world average level.

The North China Plain (NCP) is one of the most important agricultural regions in China, providing about 20% of China's total grain productionproviding about 20% of China's total grain production (Yuan and Shen, 2013). However, the NCP is also one of the areas with the greatest water shortages in China. To offset the water deficit, the high crop productivity in the NCP depends largely on groundwater irrigation (Zhang et al., 2004). In the NCP, approximately 70% of the pumped groundwater is consumed for agricultural irrigation and over 87% is consumed in the piedmont regions (Hu et al., 2010; Zhang, 2004). Sustainable development is greatly challenged by groundwater over-

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https://doi.org/10.1016/j.agwat.2018.03.003
Received 5 September 2016; Received in revised form 28 February 2018; Accepted 2 March 2018
Available online 14 March 2018
0378-3774/

exploitation, which is approximately 4–4.5 $km^3\,yr^{-1}$ in this region (Bu et al., 2008). The severe overexploitation of groundwater results in a quickly declining groundwater levels, together with environmental degradation and has therefore attracted many research attentions (Feng et al., 2013; Jia and Liu, 2002; Wang et al., 2009; Yang et al., 2002). Many studies have recently focused on sustainable groundwater supplies and food security (Bu et al., 2008; Cao et al., 2013; Chen et al., 2007; Du et al., 2014; Foster and Garduño, 2004; Zhang, 2004). However, the research into energy consumption and GHG emissions from pumping irrigation is less. This paper presents a quantitative estimate of the change of energy consumption and GHG emissions from groundwater irrigation in the NCP. The specific objectives of this paper are as follows: (a) to estimate the related cost of pumping irrigation including energy consumption and GHGs reduction costs; (b) to investigate the changes in energy consumption and GHG emissions caused from groundwater level declines; (c) to analyze the factors influencing fluctuations in groundwater and energy consumption; and (d) to clarify the importance of water- saving irrigation.

2. Data and methods

2.1. Site description

The North China Plain (NCP) is also referred to as the Huang-Huai-Hai Plain. From the viewpoint of water resource management and economic importance, a narrower definition of the NCP is more commonly used. It is the region bordered on the north by the Yan Mountains, on the west by the Taihang Mountains, to the south by the Yellow River and to the east by the Bohai Gulf. It is located in the eastern coastal region of China between 34°46–40°25′N latitude and 112°30′–119°30′ E longitude (Fig. 1). The total area of this narrowly defined NCP is 1.39×10^5 km^2, with a population of approximately 111 million. Because of the monsoon influence, rainfall is highly variable. The mean annual average precipitation is 550–650 mm, 80% of which occurs from June to September. The annual pan evaporation is approximately 1000–1500 mm. The proportion of evaporation from April to June to that of the full year is approximately 45%. The NCP contains 9% of China's population and 11% of its arable land, and produces 10% of the nation's gross domestic agricultural products. Currently 71% of its cultivated land is irrigated, with an irrigated area of 7.5 Mha.

2.2. Data sources

The average annual precipitation and temperature (1996–2013) were obtained from the Meteorological Bureau. Data on agricultural development (1996–2013), including grain output, grain value and grain planting area were obtained from the Ministry of Agriculture. Crop pattern data (1996–2013) were from National Bureau of Statistics. Data on water consumption for agriculture (1996–2013) were collected from the Water Resources Bulletin. Irrigation data (1996–2013), including the total irrigated area (1996–2013) and water-saving irrigated area (2004–2013), were collected from the National Bureau of Statistics. Average groundwater levels (1996–2013) were calculated based on data from China's Ground Water Information Center (195 observation wells selected in the NCP, of which 29 were in Beijing municipality, 21 in Tianjin municipality, 81 in Hebei province, 26 in Henan province and 38 in Shandong province). Data on the number of wells (1960s–2011) were acquired from Water Resources Yearbook. Data on groundwater exploitation (1996–2013), were collected from the Water Resources Bulletin. Electricity prices (2006–2013) in different districts were obtained from the Annual Report on Electricity Regulation. Data on groundwater levels and shallow groundwater extraction for 880 observational wells in the Hebei Plain were collected from the Hebei Department of Water Conservation (1950s–2013) (Table 1).

2.3. Estimation of pumping lifts

There are no valid statistics on groundwater pumping lifts in the NCP. Pump lifts (Y) were estimated by using the groundwater levels (X) based on data taken from 366 surveyed villages in Northern China (Wang et al., 2012a,b). The linear regression is shown in Eq. (1) and its coefficient of determination is $R^2 = 0.62$.

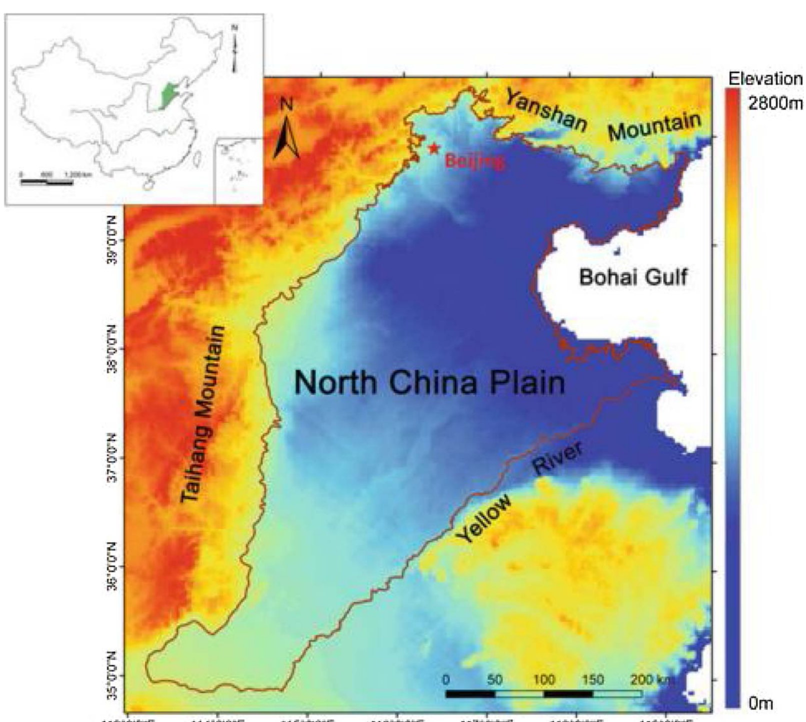

Fig. 1. Location of the study area, the North China Plain.

Table 1
Data types and sources.

Data application	Data	Time range	Data source
meteorological data	average annual temperature	1996–2013	Meteorological Bureau
	average annual precipitation	1996–2013	
agricultural development	grain output	1996–2013	Ministry of Agriculture
	grain value	1996–2013	
	grain planting area	1996–2013	
	crop pattern data	1996–2013	National Bureau of Statistics
	water consumption for agriculture	1996–2013	Water Resource Bulletin
irrigation data	total irrigated area	1996–2013	National Bureau of Statistics
	water-saving irrigated area	2004–2013	
groundwater information	average groundwater levels	1996–2013	China's Ground Water Information Center
	number of wells	1960s–2011	Water Resource Bulletin
	groundwater exploitation;	1996–2013	
energy cost	electricity price	1996–2013	Annual Report on Electricity Regulation
data of Hebei	groundwater levels and shallow groundwater extraction for 880 observational wells in the Hebei Plain	1950s–2013	Hebei Department of Water Conservation

$$Y = 0.906X + 21.75 \tag{1}$$

In this study, the average groundwater levels were calculated using data from China's Groundwater Information Center based on 195 observation wells. To verify the accuracy of the calculation, we compared our data with the Groundwater Bulletin for a particular area. The results indicated that there was a well consistency. Based on the above data for groundwater levels (1996–2013), the groundwater pumping lifts were estimated.

2.4. Estimation of agricultural groundwater consumption

Detailed and comprehensive information on actual groundwater consumption for irrigation are unavailable. The most appropriate data are the provincial level statistics of total agricultural water consumption reported in the Water Resources Bulletin. We assume that the water consumption per unit area is similar across all the irrigated area, regardless of the water source. Therefore, the proportion of total agricultural water derived from groundwater was estimated by the percentages of groundwater irrigated land relative to the total irrigated land (Eq. (2)).

$$\text{groundwater consumption} = \text{total water consumtion} \times \text{groundwater irrigated land\%} \tag{2}$$

The percentages were obtained from a national monitoring station administered by the Ministry of Agriculture, from interviews with officials in the Water Resources Bureaus and from further generalizations in the published literature (Huang et al., 2009; Wang et al., 2012a,b; Xu, 2003; Zhang et al., 2007).

2.5. Estimation of energy use rate

The energy use rate of irrigated land varies with the depth of groundwater being pumped, irrigation system, and the water requirements of grain. For the calculation of energy consumption in pumping processes, three methods are assessed (Karimi et al., 2012; Lin, 1984; Rothausen and Conway, 2011). Here, we focused on energy consumption in the extraction of groundwater. On the basis of irrigation conditions in the NCP and on data availability, the method of Lin (1984) was chosen for the following calculation (Eq. (3)):

$$\text{Energy use rate} = \frac{9.8 \times \text{Lift}}{3.6 \times 10^6 \times \text{Efficiency}} \tag{3}$$

where the unit is in kWh m^{-3} for energy use rate and percent for efficiency, respectively.

Energy consumption was calculated by first identifying the types of energy sources used. Agricultural machines in the NCP mainly included electric motors and diesel engines. This study assumed that the proportion of electric and diesel pumps were 76% and 24% in Beijing and Tianjin, 10% and 90% in Hebei, 67% and 33% in Henan, 100% and 0 in Shandong, respectively (Wang et al., 2012a,b). With a 100% efficient process, the energy needed to lift 1 km^3 of water up 1 m is 2.72×10^6 kWh. However, efficiency losses in pumping are likely to make the conversion from actual to theoretical pump efficiency achieve 40% or lower levels. Given a lack of detailed information on pumping efficiency of the individual pumps, we selected commonly used efficiency values of 15% and 40% for diesel and electric pumps, respectively, in northern China, according to Wang et al. (2012a,b). Once groundwater is pumped to the surface, further losses will occur in both the transmission and distribution (T&D) processes. This is particularly the case for electricity, where losses can be considerable (Shah et al., 2009). The T&D of energy losses are believed to range from 10 to 19% in China (Sun, 2006). We adopted a mid-range value of 14.5% for T&D efficiency losses.

2.6. Estimation of GHG emission rate

GHG emissions from groundwater irrigation were determined by estimating CO_2 emissions due to energy consumed for pumping irrigation. Direct and indirect emissions of GHGs, such as CH_4 and N_2O, are not strongly associated with energy consumption. Here, we focused on CO_2 emissions from energy consumption. The United Kingdom Department of Environment, Food and Rural Affairs/Department of Energy and Climate Change established GHG conversion factors for diesel and electricity produced that are 0.32021 kg CO_2e kWh^{-1} and 0.94773 kg CO_2e kWh^{-1} in China (Wang et al., 2012a,b). This study used these figures and a revised equation (Eq. (4)) from Wang et al. (2012a,b) to calculate the average GHG emissions rate (kg CO_2e m^{-3}) based on a combination of power sources for pumps in the NCP, as follows (Fig. 2):

$$\text{GHG emission rate} = \text{Energy use rate}_{\text{Electric}} \times 0.95 + \text{Energy use rate}_{\text{Diesal}} \times 0.32 \tag{4}$$

where the unit is kg CO_2e m^{-3} for the GHG emission rate, and kWh m^{-3} is the energy use rate, respectively.

3. Results

3.1. Changes in groundwater levels and agricultural groundwater consumption during 1996–2013

3.1.1. Agricultural groundwater consumption

During 2003–2013, the NCP experienced a substantial increase by nearly 45% in grain output (Fig. 3). The average increment rate was

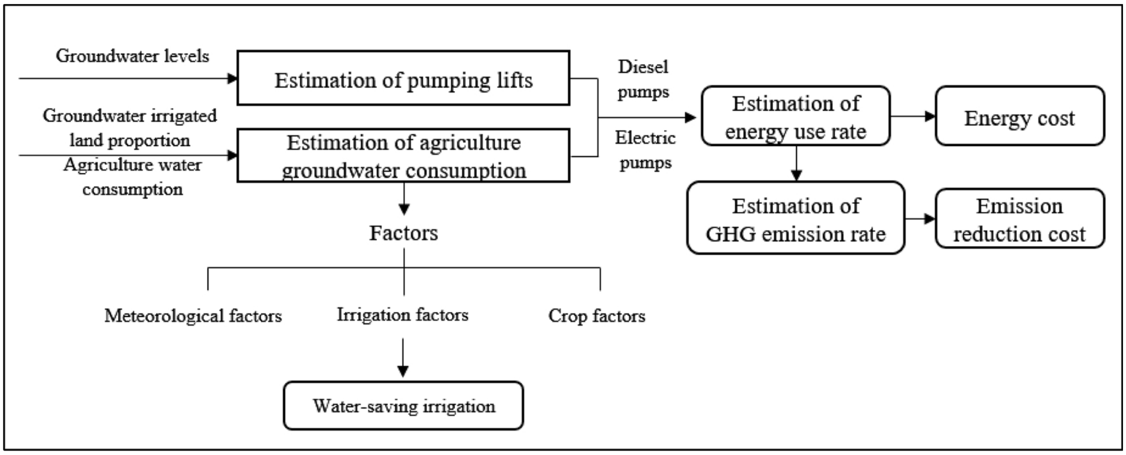

Fig. 2. Flow chart of the methods.

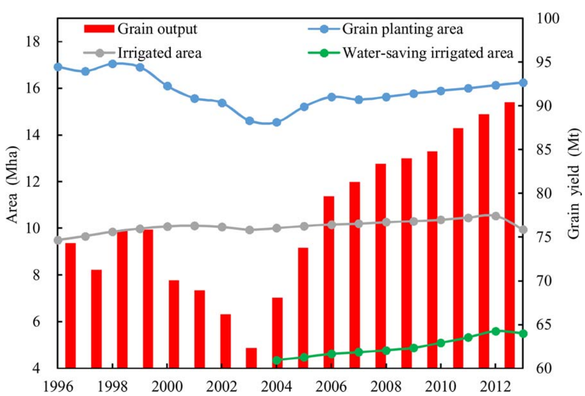

Fig. 3. Changes in grain output, grain planting area, irrigated area and water-saving irrigated area in NCP during 1996–2013. Data on irrigated area and water-saving irrigated area were from the National Bureau of Statistics. Grain output and grain planting area were from the Agricultural Bureau. There were no data for water-saving irrigated area before 2004.

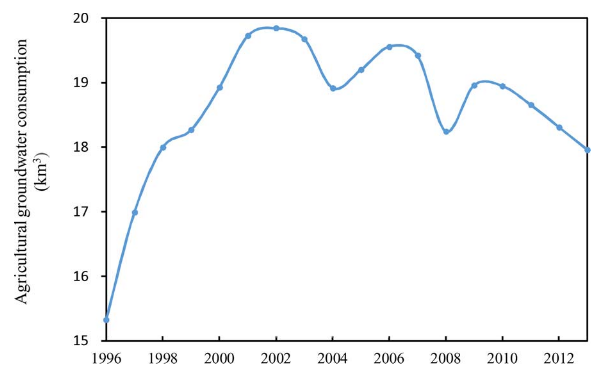

Fig. 4. Changes in agricultural groundwater consumption in the NCP during 1996–2013.

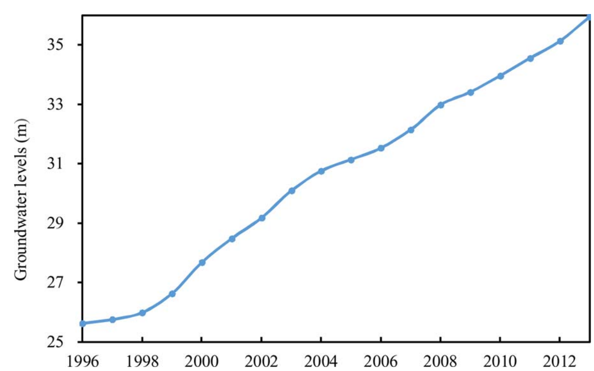

Fig. 5. Changes in groundwater levels in the NCP during 1996–2013. Calculation was based on 195 observation wells, and groundwater levels were obtained by weighting groundwater level of each district by its plain area. These observation wells were representatively located on the piedmont plain, median plain and coastal plain.

2.8 Mt yr^{-1}, which was coincided with growth of grain planting area. Higher planting area resulted in an increase in irrigated area. During 1996–2013, irrigated area in this region increased from 8.99 Mha to 9.45 Mha, at a rate of 0.03 Mha yr^{-1}. Area under water-saving irrigation techniques increased by roughly 30% from 3.85 Mha in 2004 to 4.99 Mha in 2013. The proportion of water-saving irrigated area to the total correspondingly increased.

A total of 67% of the water supply from surface runoff and groundwater had been used for irrigation in the NCP. Irrigation accounts for over 70% of the total groundwater withdrawn. Over the last 15 years, two obvious periods of agricultural groundwater consumption in the NCP could be seen. It was 15.33 km^3 in 1996 and reached a maximum of 19.84 km^3 in 2002, an increase of 0.75 km^3 yr^{-1} (Fig. 4). Since 2003, agricultural groundwater use appeared a decreasing trend, with two significant drops in 2004 and 2008. The distinct increase of precipitation in 2004 and 2008 (data not shown) may play an important role in these significant drops.

3.1.2. Groundwater level declines

With the expansion of groundwater irrigation, the number of motor-pumped wells sharply increased from 1.8 thousand in the 1960s to 0.83 million in the early 2000s. The density of pumped wells had reached more than 20 per km^2 in the early 2000s. In the 2000s, the groundwater exploitation rate (the ratio of groundwater withdrawals to groundwater recharge) in many parts of the NCP exceeded 100%, and in some areas, the ratio exceeded 150% (Liu et al., 2010). Persistent groundwater overexploitation in the NCP had resulted in increasingly serious water-level declines.

Groundwater levels (represented as positive values, similarly hereinafter) dropped from 25.62 m in 1996 to 35.94 m in 2013, declining at a rate of 0.61 m yr^{-1} (Fig. 5). In intensively groundwater-irrigated districts, the groundwater levels declined at a rate faster than 1 m yr^{-1}.

3.2. Changes in energy consumption and GHG emissions from pumping irrigation

In the NCP, due to groundwater level declines, pumping became increasingly energy-intensive and emitted more GHGs. As shown in Table 2, data about pump lifts, agricultural groundwater consumption, energy use rate, and energy consumption were used to establish energy

Table 2
Pump lifts, agricultural groundwater consumption, energy use and GHG emissions from pumping irrigation in the NCP during 1996–2013.

year	Groundwater levels (m)	Pump lifts[a] (m)	Agricultural groundwater consumption (km^3 yr^{-1})	Energy use rate (kWh m^{-3})[b]			Energy consumption[c] (10^9 kWh)	GHG emission rate (kg CO_2e m^{-3})[d]	GHG emission (Mt CO_2e)[e]
				Diesel	Electric	Total			
1996	25.62	44.96	15.33	0.23	0.27	0.5040	7.72	0.4018	6.16
1997	25.75	45.08	16.99	0.23	0.27	0.5053	8.59	0.4038	6.86
1998	25.99	45.29	18.00	0.23	0.28	0.5077	9.14	0.4046	7.28
1999	26.63	45.87	18.27	0.24	0.28	0.5142	9.39	0.4062	7.42
2000	27.68	46.83	18.92	0.24	0.28	0.5249	9.93	0.4184	7.92
2001	28.48	47.55	19.72	0.24	0.29	0.5330	10.51	0.4249	8.38
2002	29.17	48.18	19.84	0.25	0.29	0.5401	10.72	0.4305	8.54
2003	30.09	49.01	19.67	0.25	0.30	0.5494	10.81	0.4379	8.62
2004	30.76	49.62	18.92	0.25	0.30	0.5561	10.52	0.4433	8.39
2005	31.14	49.96	19.20	0.26	0.30	0.5600	10.75	0.4464	8.57
2006	31.53	50.32	19.56	0.26	0.31	0.5640	11.03	0.4496	8.79
2007	32.14	50.87	19.42	0.26	0.31	0.5702	11.07	0.4556	8.85
2008	32.98	51.63	18.24	0.26	0.31	0.5787	10.56	0.4613	8.42
2009	33.42	52.02	18.96	0.27	0.32	0.5831	11.06	0.4665	8.84
2010	33.97	52.52	18.95	0.27	0.32	0.5887	11.16	0.4693	8.89
2011	34.55	53.06	18.66	0.27	0.32	0.5947	11.09	0.4800	8.95
2012	35.13	53.58	18.31	0.27	0.33	0.6006	11.00	0.4787	8.76
2013	35.94	54.31	17.96	0.28	0.33	0.6088	10.93	0.4853	8.72

[a] Column 3 = 0.906 × column 2 + 21.75.
[b] Efficiency of diesel was 15%, electric was 40%, and T&D loss was 15%. The proportion of electric and diesel pumps were set to 76% and 24% during 1996–2013.
[c] Column 8 = column 4 × column 7.
[d] GHG conversion factors: 0.94773 kg CO_2e kWh^{-1} for electricity, 0.32021 kg CO_2e kWh^{-1} for diesel.
[e] Column 10 = column 4 × column 9.

consumption and GHG emissions. During 1996–2013, the pump lifts increased by 21%, which coincided with groundwater level declines by 10.32 m. The energy use rate for pumping irrigation increased continuously from 0.50 kWh m^{-3} to 0.61 kWh m^{-3} by nearly 22% during 1996–2013. In addition, agricultural groundwater consumption increased by 20% during this period. The GHG emissions in 2013 were 8.72 Mt CO_2e; it was almost 1.5 times that of 1996 (6.16 Mt CO_2e). There was a temporary decrease in GHG emissions in 2004 and 2008, which indicated a similar trend in agricultural groundwater consumption.

Using data of grain output, energy consumption and GHG emissions, energy use intensity and GHG emission intensity were evaluated. Energy use intensity rapidly increased since 1996 (103.99 kWh t^{-1}) and peaked in 2003 (173.42 kWh t^{-1}) (Fig. 6a). During 1996–2003, GHG emission intensity had similar trend, with a 66.7% increase (Fig. 6b). Then, energy use intensity and GHG emission intensity progressively had declined. The decreasing trend since 2004 was caused by rapid increase in grain production (Fig. 3), which might be results of efficiency increase in water and energy uses. From a broader planning perspective, it is critical to analyze the factors underlying the falling intensities of energy use and GHG emissions in this region.

3.3. Spatiotemporal characteristics of energy consumption and GHG emissions in the NCP

3.3.1. Spatial changes of energy consumption and GHG emissions

The energy consumption and GHG emissions in the five districts (referring to the parts of the plains belonging to the NCP, similarly hereinafter) are listed in Table 3. Different districts exhibited impressive differences in GHG emission rate, with a range of 0.38–0.55 kg CO_2e m^{-3} because GHG emission rate reflected a mix of pump lifts and power sources (diesel or electric). Tianjin had the highest GHG emission rate (0.55 kg CO_2e m^{-3}), which coincided with the greatest pump lift (61.45 m). However, in Shandong, almost all of the pumps were electric powered, which caused its GHG emission rate to increase from equal to the lowest energy use rate (0.41 kWh m^{-3}) to the third lowest GHG

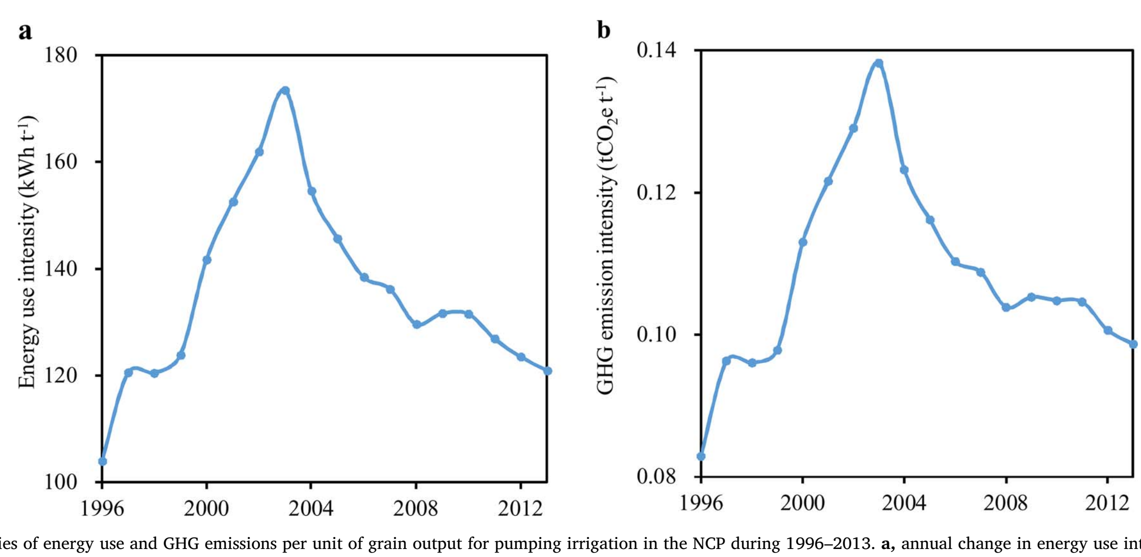

Fig. 6. Intensities of energy use and GHG emissions per unit of grain output for pumping irrigation in the NCP during 1996–2013. **a,** annual change in energy use intensity. **b,** annual change in GHG emission intensity. The estimates of energy use and GHG emissions divided by grain output provided the intensities of energy use and GHG emissions.

Table 3
Pump lifts, agricultural groundwater consumption, energy use and GHG emissions from pumping irrigation in each district in 2013.

District[a]	Groundwater levels (m)	Pump lifts (m)	Intensity of agricultural groundwater consumption[b] ($m^3\,ha^{-1}$)	Energy use rate[c] ($kWh\,m^{-3}$)	GHG emission rate ($kg\,CO_2e\,m^{-3}$)	GHG emissions ($Mt\,CO_2e$)
Beijing	24.30	43.77	5750.88	0.49	0.38	0.35
Tianjin	43.82	61.45	1068.41	0.69	0.55	0.18
Hebei	42.97	60.68	2721.15	0.57	0.50	5.80
Henan	13.20	33.71	441.18	0.57	0.30	0.66
Shandong	32.02	50.76	634.38	0.41	0.39	1.16

[a] The region included the plains in Beijing,Tianjin, Hebei province, and the northern parts of the plains in Shandong and Henan provinces (north of the Yellow River).
[b] Using data on irrigated area and agricultural groundwater consumption, the intensity of agricultural groundwater consumption was evaluated.
[c] The distribution of electric and diesel pumps was basically set to 76% and 24% in Beijing and Tianjin, 10% and 90% in Hebei, 67% and 33% in Henan, and 100% and 0 in Shandong.

emission rate ($0.39\,kg\,CO_2e\,m^{-3}$). This results indicated the importance of power source. Hebei was the largest contributor to GHG emissions by far, responsible for 69%, due to its mix of higher pump lift and the second highest intensity of agricultural groundwater consumption.

3.3.2. Temporal changes in energy consumption and GHG emissions

Rapid groundwater level declines had been taking place in each district, with a corresponding increase in energy use rate and GHG emission rate over the past 18 years (Fig. 7a). Hebei and Beijing had the highest rate of groundwater level declines by approximately $0.8\,m\,yr^{-1}$ in the 2000s. Therefore, the magnitude of changes in energy use rate in Hebei and Beijing were much larger than in the other three districts during 1996–2013 (Table 4). It was noteworthy that energy consumption and GHG emissions exhibited a reduction in Beijing, Tianjin and Shandong in the 2000s (Fig. 7b).

3.3.3. Relationships among groundwater levels change, pumping energy consumption, and GHG emissions in a typical district in last 60 years

The Hebei Plain had the most serious groundwater level declines and the largest GHG emissions volume from pumping irrigation (Table 4). During recent decades, the number of active wells increased rapidly. For example, in 1960, there were 0.04 million wells in the Hebei Plain, in 1980, there were 0.40 million, and in 2010, there were 0.92 million, which represents a 22-fold increase over the past 50 yrs. Over 80% of the active wells were used for agricultural irrigation. In the 2000s, the annual exploitation of groundwater in the Hebei Plain reached up to $13.6\,km^3$, and the annual overexploitation volume reached up to $3.8\,km^3$. The annual decline in groundwater levels was over 0.4 m in the 1970–1980s, 0.6 m in the 1990s and 0.9 m in the 2000s. Since 1950, a significant correlation (r = 0.995, α = 0.01) between groundwater levels and cumulative agricultural groundwater consumption in this region implied that pumping irrigation was likely a major contributor to groundwater level declines (Fig. 8).

In Hebei Plain, groundwater levels decreased from about 20 m in 1955 to 45 m in 2013 (Fig. 9a), while the corresponding energy use rate for pumping irrigation increased by almost more than 0.5 times from 0.37 to $0.57\,kWh\,m^{-3}$ during 1955–2013 (Fig. 9b). Time was divided as three stages during 1955–2013 by GHG emissions in Hebei Plain. During 1955–1995, energy consumption increased slowly at a rate of $0.04 \times 10^9\,kWh\,yr^{-1}$; during 1996–2007, the average incremental rate increased about six times to $0.23 \times 10^9\,kWh\,yr^{-1}$; since 2008, energy consumption changed irregularly due to fluctuations in the volume of groundwater consumption (Fig. 9c, d), although the energy use rate continued to increase.

3.4. Influencing factors on energy consumption and GHG emissions

One objective of this study was to clarify the factors influencing energy consumption and GHG emissions. Results of regression analysis showed that there was a significant correlation (r = 0.994, α = 0.01) between the cumulative groundwater consumption and groundwater levels during 1996–2013 (Fig. 10a). This result suggested that for every $1\,km^3$ groundwater use, groundwater level would fall 0.033 m in the NCP. Furthermore, the close correlation between energy consumption and groundwater consumption was also found (r = 0.805, α = 0.01).

To further identify the critical factors influencing groundwater consumption, correlational analyses between precipitation and groundwater consumption were conducted. Results showed that there was a negative correlation between precipitation and groundwater consumption (r = −0.608, α = 0.05) but not in a good linear relationship ($R^2 = 0.37$) (Fig. 11). As the main replenishment sources, precipitation can certainly affect the variation of groundwater

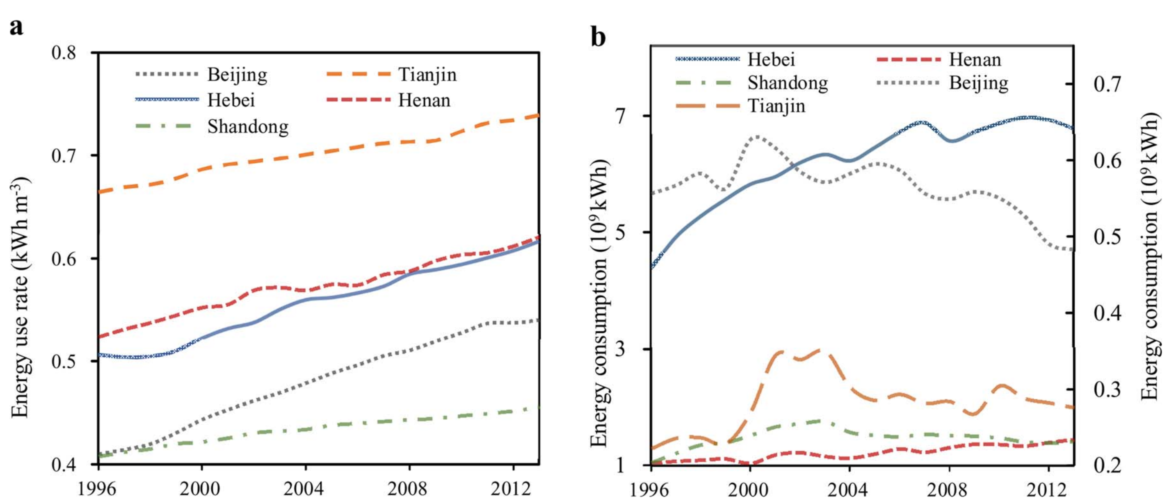

Fig. 7. Changes in energy use rate and energy consumption for pumping irrigation in five districts during 1996–2013. **a,** energy use rate in each district. **b.** energy consumption in each district-primary axis represents the values of Hebei, Henan and Shandong province; y-secondary axis represents the values of Beijing and Tianjin municipalities.

Table 4
The variation of groundwater level declines, energy use and GHG emissions in each district during 1996–2013.

District	Groundwater declines (m)	Agricultural groundwater use (km^3)	Energy use rate ($kWh\,m^{-3}$)	Energy consumption (10^9 kWh)	GHG emissions (Mt CO^2e)
Beijing	12.86	−0.53	0.13	−0.08	−0.05
Tianjin	7.32	0.05	0.08	0.05	0.06
Hebei	13.11	2.10	0.11	2.41	1.98
Henan	6.31	0.40	0.09	0.40	0.21
Shandong	6.69	0.61	0.05	0.36	0.35

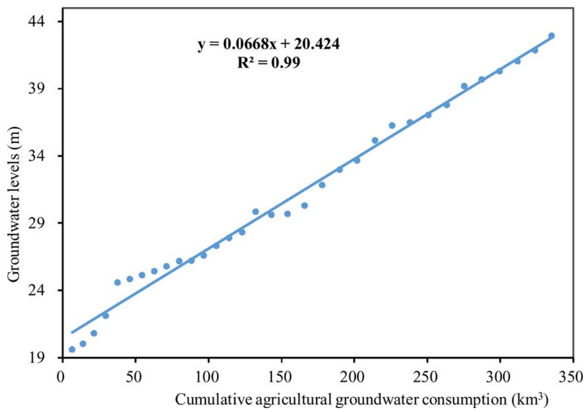

Fig. 8. Relationship between groundwater levels and cumulative agricultural groundwater consumption in Hebei Plain during 1955–2013. There was a significant linear correlation ($R^2 = 0.99$) between groundwater levels and cumulative agricultural groundwater consumption in this region.

consumption in a long term (Fig. 12, Table 5). In addition, over time the sensitivity of groundwater consumption variation to precipitation decreased in wet year and increased in dry year. The results indicated that precipitation supply function weakened when it was sufficient.

The relationship between agricultural groundwater consumption and crop patterns were studied. Grains were the main crop species in NCP, The planting area of grains accounts about 70% of the total crops planting area (Fig. 13). The proportion of grains' planting area did not change a lot during the period and there is no correlation between it and groundwater consumption. Wheat and maize are the main grain species and they consume most water in NCP. Cotton is the third water consumption crop and its specific water consumption is the highest (Luo et al., 2015). However, the groundwater consumption did not correlate to the planting area of wheat or cotton. There was a strong negative correlation between groundwater consumption and planting area proportion of maize ($R^2 = 0.49$). Maize is not the least water needed crop (third out of five major crops) according to Luo et al. (2015). Its increase during 2002–2013 should have not decrease the groundwater consumption. Therefore, we assume there are some factors that affect groundwater consumption more.

Then we chose grain economic value, grain output, irrigated area and percentage of water-saving irrigated area as the main factors and studied the relationship between them and groundwater consumption. Correlational analyses showed that there was significant correlation between groundwater consumption and grain value ($r = -0.776$, $\alpha = 0.01$), grain output ($r = -0.764$, $\alpha = 0.01$), but not irrigated area ($r = 0.141$). Agricultural groundwater consumption decrease as grain value and output increase (Fig. 14a, b).

In fact, agricultural groundwater consumption had a strong negative correlation (Fig. 14d, $R^2 = 0.64$) with the percentage of water-saving irrigated area. The results indicated that the percentage of water-saving irrigation was the critical element of groundwater consumption during 2002–2013. So the smaller increasing rate of groundwater and energy consumption could be closely related to water-saving irrigation, in recent years. That's also why the groundwater consumption did not increase when the grain output increase.

Strong linear relationship between them (Fig. 15b) indicated that an average 1% more percentage of water-saving irrigation area would increase 0.13 $kg\,m^{-3}$ production efficiency of groundwater (the ratio of crop production to agricultural groundwater consumption). This results indicated the feasibility of water-saving irrigation as a measure to maintain food production and save water.

3.5. Economic cost of energy consumption and GHG emissions caused by groundwater level declines

In this study, the total cost only included fuel and electricity. Costs on fixed investment, repairs, and maintenance were not included because these data are difficult to obtain. Most of the energy for pumping irrigation in the NCP came from electricity (76%), and a smaller share derives from diesel-power (24%). To estimate the cost of diesel for pumping irrigation, we referenced the energy equivalent of diesel fuel (0.064 $L\,kWh^{-1}$) in other countries (Yilmaz et al., 2005). The cost reported were adopted and converted into US$ using annual exchange rates.

As shown in Table 6, for unit groundwater consumption, cost increased from 0.018 US$ m^{-3} from 0.030 US$ m^{-3} for electricity use and from 0.010 US$ m^{-3} to 0.025 US$ m^{-3} for diesel use during 2006–2013. On the whole, the cost of energy consumption for pumping irrigation had nearly doubled within seven years. The high cost rendered irrigation unaffordable for the farmer. In addition, it was shown that diesel pump is less efficient than electric pump. In 2013, unit energy cost of electric pump was 0.09 US$ kWh^{-1}, while it was 0.12 US $ kWh^{-1} (1.42 US$ L^{-1}) for diesel. In addition, diesel price rose faster than electricity price. During 2006–2013, the price of electricity and diesel increased respectively by 52.5% and 136.7%. To reduce cost, more electric pump should be used to replace the diesel pump in the NCP.

Furthermore, we analyzed its GHG emission cost. Price in the national emissions trading scheme (ETS) was 12.22 EUR€ (14.67 US$) per tonne by the end of 2011. The 2015 China Carbon Pricing Survey released by the China Carbon Forum showed that the prices were expected to be US$ 6.29–11.67 per tonne of CO_2 emitted during 2017–2025. Based on the above understanding, this study assumed a marginal carbon abatement cost was US$ 10 per tonne. Accordingly, the abatement cost of GHG emissions from groundwater pumping (8.72 Mt CO_2e) was US$ 0.087 billion in 2013.

4. Discussion

As cumulative groundwater consumption increases during past decades, the groundwater levels have declined in North China Plain dramatically (Fig. 9a). For every 1 km^3 groundwater consumption, groundwater level would fall 0.033 m in the NCP. During 1996–2013, groundwater level here declined from 25.62 m to 35.94 m. Moreover, in recent years, groundwater levels showed accelerating declines. The decline rate was 0.34 $m\,yr^{-1}$ in the 1990s and almost doubled to 0.64 $m\,yr^{-1}$ in the 2000s. Declined groundwater levels makes the pumping irrigation more energy intensive and emitting more GHGs.

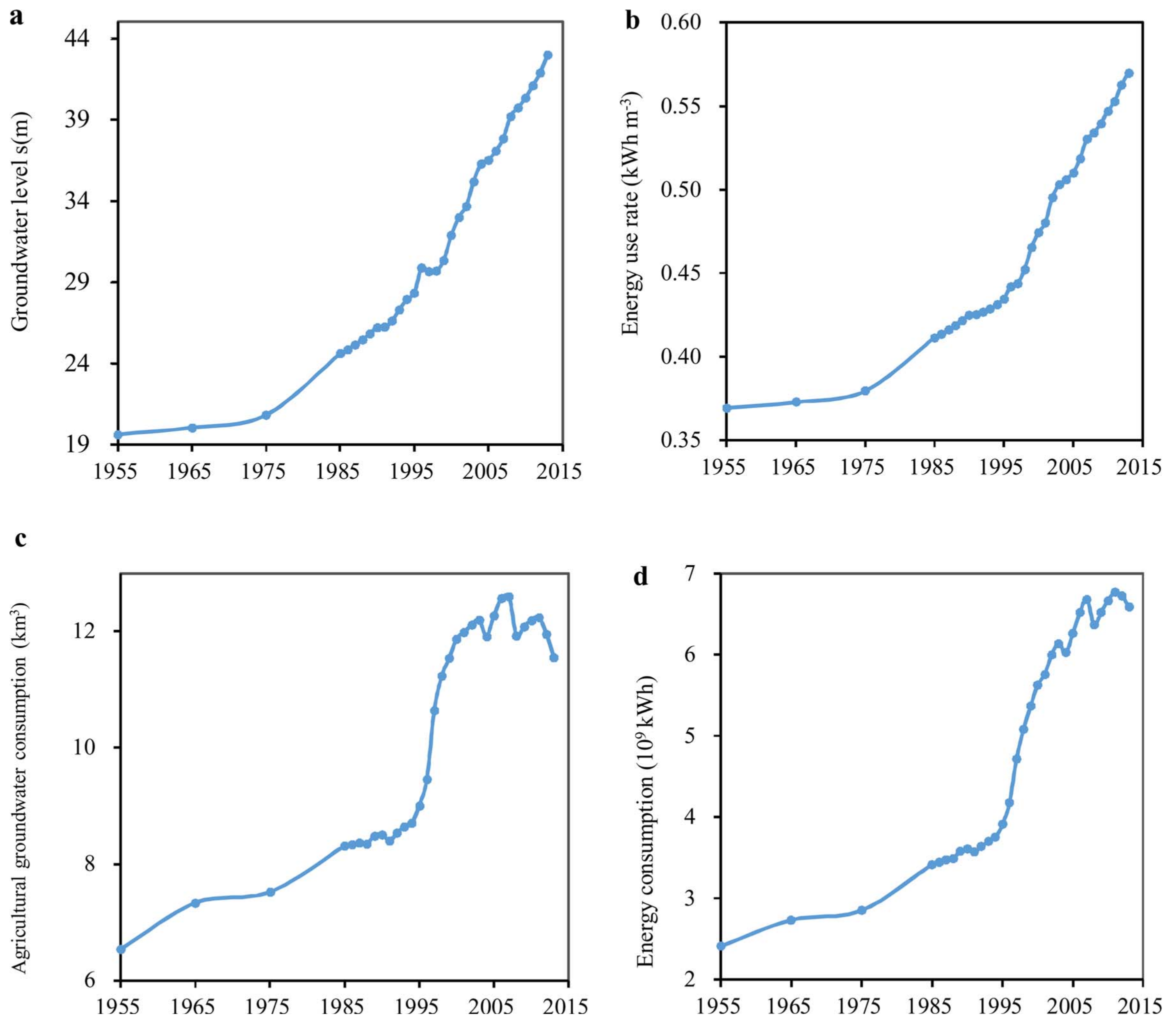

Fig. 9. The changes in groundwater levels, energy use rate, agricultural groundwater consumption, and energy consumption in Hebei Plain during 1955–2013. **a,** the changes in groundwater levels. Groundwater levels (1955–1995) were estimated based on data of 880 observational wells, which were collected from the Hebei Department of Water Conservancy. Due to a lack of integrity, data on groundwater levels before 1985 were used only for 1955, 1965, 1975, and 1980. **b,** the changes in energy use rate. **c**, the changes in agricultural groundwater consumption and **d**, the changes in energy consumption.

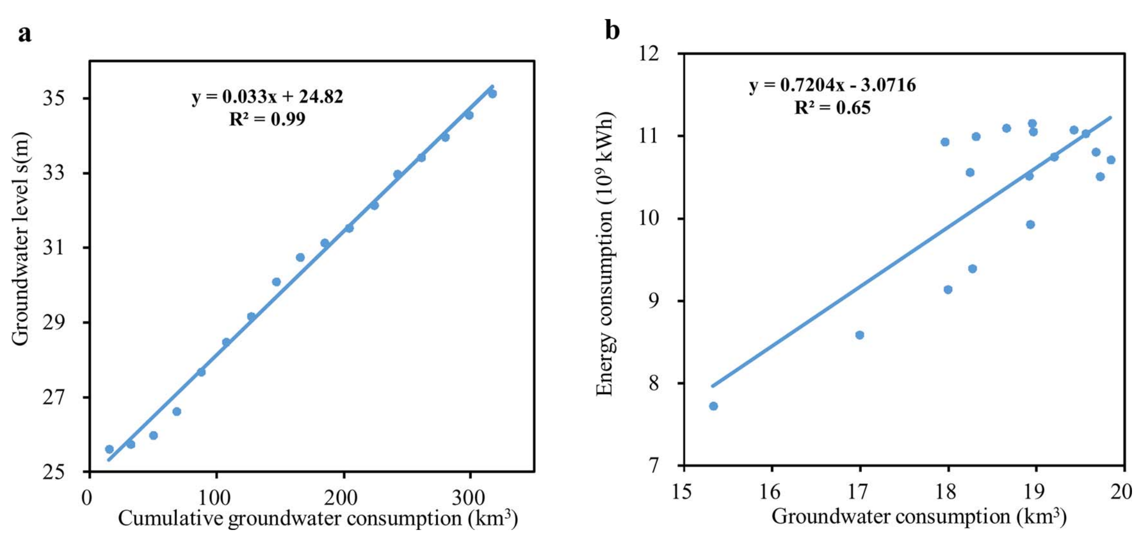

Fig. 10. a, relationship between the cumulative groundwater consumption and groundwater levels and **b,** relationship between groundwater consumption and energy consumption in the NCP.

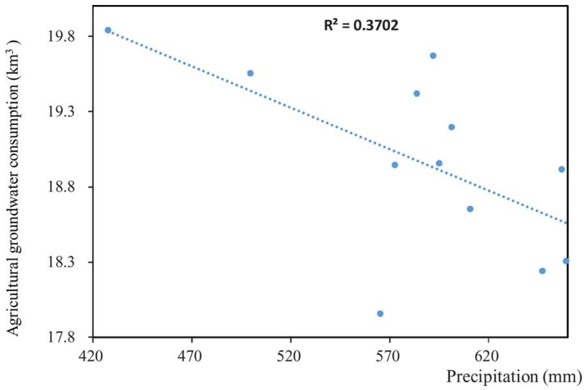

Fig. 11. Relationship between precipitation and groundwater consumption for agriculture in the NCP. There was a weak correlation (R^2 = 0.37) between precipitation and Agricultural groundwater consumption in the NCP.

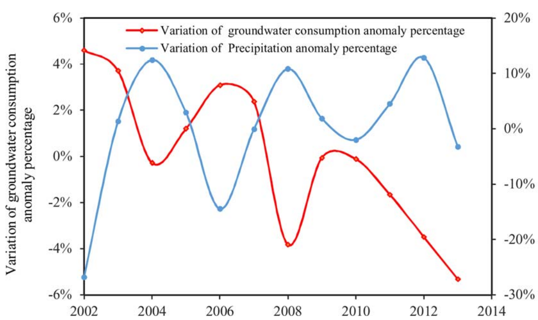

Fig. 12. Variation of precipitation and groundwater consumption anomaly percentage during 2002–2013 in the NCP.

Table 5
The variation of groundwater levels in the wet and dry years.

Wet year[a]	2004	2008	2012
Variation in the year (m)	**−0.76**	**−1.18**	**−0.35**
Variation before this year (m)	−0.17	−0.14	−0.29
Variation after this year (m)	0.28	0.72	−0.35
Dry year[b]	2002	2006	
Variation in the year (m)	**0.22**	**0.36**	
Variation before this year (m)	0.11	0.28	
Variation after this year (m)	−0.21	−0.14	

[a] In wet year, variation of precipitation anomaly percentage is more than 10%.
[b] In dry year, variation of precipitation anomaly percentage is less than −10%.

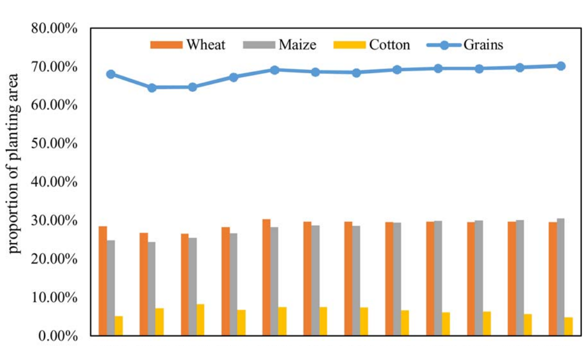

Fig. 13. Proportion of grains planting area in NCP during 2002–2013.

4.1. Increasing energy consumption and cost caused by groundwater level declines

There was a significant positive linear relationship between energy consumption and groundwater levels in NCP (Eq. (3)). More energy was required for pumping from lower groundwater. The energy needed to pump 1 m^3 water increased from 0.5040 kWh in 1996 to 0.6088 kWh in 2013. The total energy consumption in the whole NCP also increased from 7.72×10^9 kWh to 10.93×10^9 kWh simultaneously. Increasing energy consumption led to the increasing energy cost. Within the seven years (2006–2013), pumping cost increased straightly and nearly doubled. Until 2013, the farmer must pay US$ 0.055 for 1 km^3 groundwater consumption. From the point of the total cost, it was as much as US$ 1.15 billion in 2013 in the NCP, reaching up to 9.6% of the local GDP. On the other hand, farmers are still deepening their wells to maintain their cropland under irrigation. If the groundwater levels continue decreasing, the cost of pumping irrigation would be quite a burden for farmers in the future. Increased cost of irrigation is negatively affecting farmers' incomes (Bhuyan, 2004; Pimentel et al., 2002). Cost increasing can make farmers difficult to decide whether to plant high yield grain crops, or plant high-value economic crops, which would in turn affect the food security.

The cost of electric pump is always higher than diesel pump during our study period. It was 0.030 US$ m^{-3} for electricity use and 0.025 US$ m^{-3} for diesel in 2013. However, it is because the groundwater levels were lower in electric pump used areas than diesel pump used areas. To reduce cost, more electric pump should be used to replace the diesel pump in this region according to our study. In 2013, unit energy cost of electric pump was 0.09 US$ kWh^{-1}, while it was 0.12 US$ kWh^{-1} (1.42 US$ L^{-1}) for diesel. In addition, diesel price rose faster than electricity price. This was especially true in Hebei Plain (the largest energy consumer in the NCP), where almost all of the energy consumption for pumping irrigation came from diesel. There was huge potential to reduce economic cost through changing the energy structure.

Other studies also indicate that economic cost of pumping irrigation is notable and should be paid attention to. Unit pumping cost usually ranges between 0.01 US$ and 0.20 US$, depending on different pump lifts (Llamas and Martínezsantos, 2005). In Turkey, the irrigation area relies completely on groundwater resources; the irrigation cost of electricity (not limited to pumping) is found to be 744.64 US$ ha^{-1} (Topak et al., 2009). According to a field survey in North China, the farmer need to pay a flat rate of 55 US$ ha^{-1} (including equipment cost) for irrigation in Henan and 125–150 US$ ha^{-1} in Hebei (Yang et al., 2003). In the US, agriculture is the largest business consumer of both electricity and water, using most of the direct energy to pump groundwater at an annual cost of almost US$ 1.2 billion (Rothausen and Conway, 2011).

4.2. Increasing GHG emissions from pumping irrigation

Increasing energy consumption led to increasing GHG emissions. During 1996–2013, GHG emission rates increased from 0.40 $kgCO_2e$ m^{-3} to 0.49 $kgCO_2e$ m^{-3}. GHG emission rate increased annually by 1.5×10^{-3} $kgCO_2e$ m^{-3} yr^{-1} in the 1990s and 5.3×10^{-4} $kgCO_2e$ m^{-3} in the 2000s. In contrast, groundwater consumption for agriculture was no longer increased (Fig. 4). This result suggested that in recent years, same groundwater exploitation could lead to more serious declines and GHG emissions than in previous years. Groundwater was probably stored in funnel-shaped space. In the future, the NCP need to pay more to protect groundwater resources and reduce GHG emissions.

Groundwater declines were not uniformly distributed throughout the NCP and GHG emission rate exhibited impressive differences. In 2013, the estimate of GHG emission rate ranged from 0.38 kg CO_2e m^{-3} in Beijing to 0.55 kg CO_2e m^{-3} in Tianjin. It had relation with diverse groundwater levels. With more serious groundwater declines in Hebei and Beijing during 1996–2013, increase in GHG emission rate in these two districts was higher. Hebei has the largest GHG emissions due to the largest agricultural groundwater consumption. These results from this study are similar the estimates for North China (Wang et al., 2012a,b), which suggests that Tianjin has the highest GHG emission

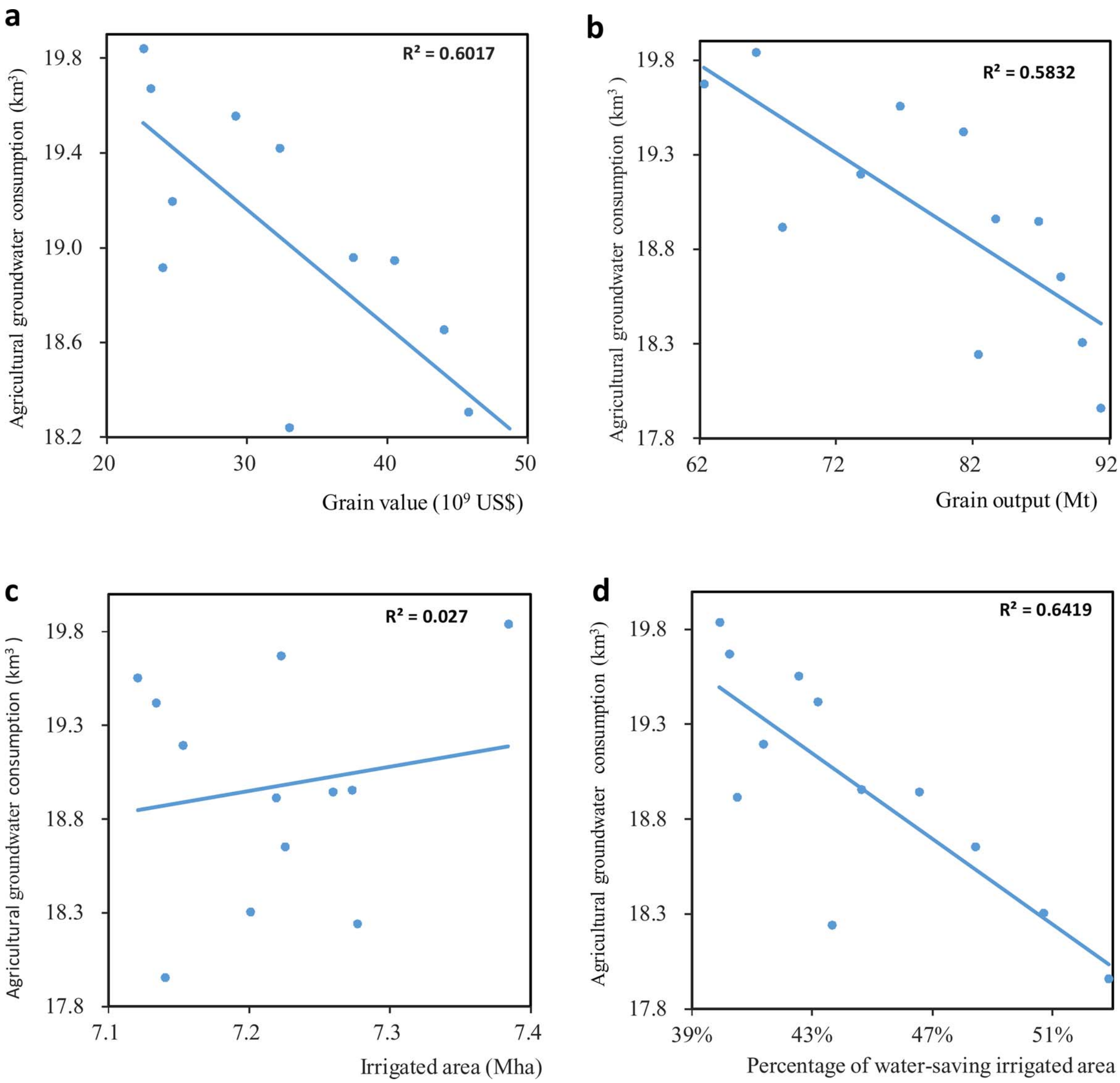

Fig. 14. The relationship between agricultural groundwater consumption and several main agricultural factors in NCP during 2002–2013. **a,** namely grain value. **b,** grain output. **c,** irrigated area. **d,** the percentage of water-saving irrigated area. Grain value allowed for inflation in view of rising prices. The percentage of water-saving irrigated area was water-saving irrigated area divided by total irrigated area.

rate and Hebei is the largest contributor to GHG emissions in the NCP. In different regions, GHG emission rates from groundwater pumping showed significant difference mainly because of diverse water depth.

When estimating economic cost of pumping irrigation, emission mitigation cost should be considered. The cost of emissions mitigation from pumping irrigation (8.72 Mt CO_2e) was US$ 0.087 billion in 2013 in this region, reaching up to 0.7% of the local GDP. According to the Paris Agreement (Climate Change Conference 2015), China should reduce GHG emissions at an annual rate of 4% until 2030. Agriculture including irrigation has been proposed as a relatively cheap source of net emission reductions (West and Marland, 2002). Therefore, it was necessary and urgent to reduce GHG emissions from groundwater pumping. In fact, there is growing interest on policy options to reduce agricultural GHG emissions (Barker et al., 2009). However, reduction cost could be high because of large emissions.

Declining groundwater levels are a matter of concern not only on water resources, but also on increased energy consumption and GHG emissions. Energy use and GHG emission rates for groundwater pumping have almost doubled, which have coincided with serious groundwater levels declines over the past 50 yr (Li et al., 2013). There has been similar effects in other regions. In India, pumping lifts become higher; for pumping per unit of groundwater, energy consumption and GHG emissions become hardly prohibitive (Kumar, 2005). In California, agriculture uses 85% of the withdrawn groundwater (15.4 km^3), and 90% of all electricity used on farms is consumed in pumping groundwater for irrigation (Cohen et al., 2004). Electricity used for pumping groundwater in California would average 2.25 billion kWh (the equivalent of 0.1370 $kgCO_2e\ m^{-3}$). With lower pump lifts (36 m) and higher pumping efficiency (70%), GHG emission rate is smaller in California than the NCP. In Iran, average extracting 1 m^3 groundwater requires 0.826 kWh of energy and 0.1 $kgCO^2e$ (Karimi et al., 2012). More than 70% of the total groundwater extraction in Iran is from deep wells with an average depth of 90 m. Therefore, groundwater exploitation in Iran is significantly more energy-intensive than that in the NCP and emits more GHG. Extensive studies have been carried out on the effect of groundwater irrigation on total emissions from the whole agriculture. Carbon footprint of the grain output is estimated in the NCP and the results indicated that the main components of carbon footprint were electricity for irrigation (30.25%) (Wang et al., 2015). Zou et al. (2013) suggested that groundwater pumping is responsible for 30.49%–42.68% of total emissions from energy activities in the agriculture sector in China.

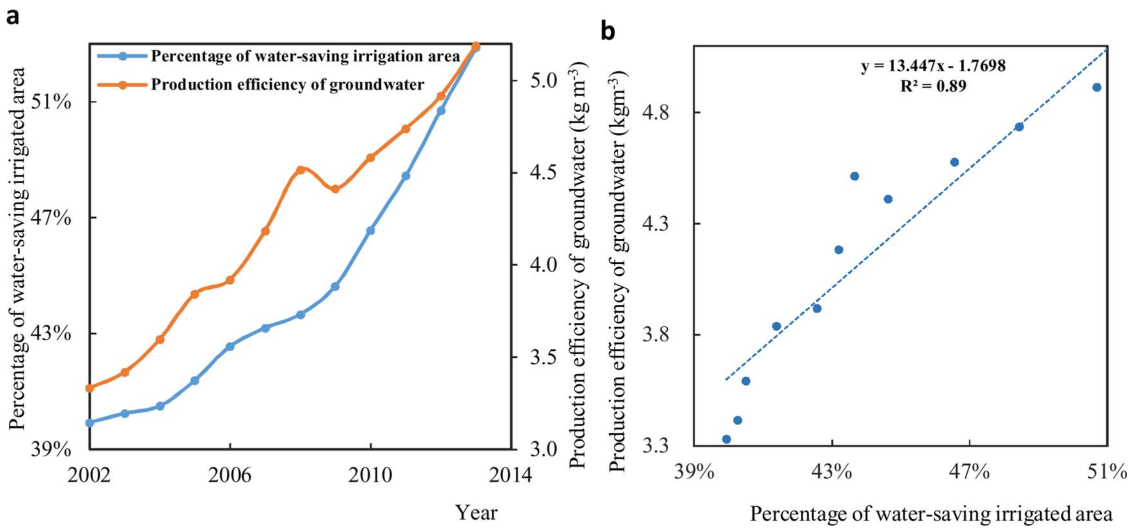

Fig. 15. The characteristics of the percentage of water-saving irrigated area and production efficiency of groundwater during 2002–2013. **a,** Changes in the percentage of water-saving irrigated area and production efficiency of groundwater. **b,** the relationship between the percentage of water-saving irrigated area and production efficiency of groundwater during 2002–2013.

Table 6
Changes in economic cost caused by energy consumption for pumping irrigation in 2006–2013 in the NCP.

Year[a]	Electricity			Diesel		
	Electricity use[b] (10^9 kWh)	Electricity sales price[c] (US\$ kWh^{-1})	Unit cost (US \$ m^{-3})	Diesel use[d] (10^9 L)	Diesel sales price[e] (US \$ L^{-1})	Unit cost (US \$ m^{-3})
2006	6.91	0.059	0.018	0.38	0.597	0.010
2007	6.99	0.065	0.020	0.38	0.683	0.011
2008	6.81	0.073	0.023	0.37	0.858	0.015
2009	6.92	0.076	0.024	0.38	1.040	0.018
2010	6.99	0.082	0.026	0.39	1.127	0.019
2011	6.98	0.084	0.027	0.38	1.241	0.022
2012	6.89	0.088	0.029	0.38	1.392	0.025
2013	6.83	0.090	0.030	0.38	1.417	0.025

[a] Statistical data on electricity prices were not available before 2006. State Electricity Regulatory of Commission was established in 2002 and first published the Annual Report on Electricity Regulation in 2006.
[b] The estimates were the weighted average of electricity sales prices in five districts. The data on electricity price by district were collected from the Annual Report on Electricity Regulation.
[c] The energy consumption of diesel-power was estimated by equation 3. Diesel consumption (L) was energy consumption of diesel-power times energy equivalent of diesel fuel (0.064 L kWh^{-1}).
[d] The data on diesel sales price were calculated based on relative notices issued by the National Development and Reform Commission.

4.3. Importance of water-saving irrigation

Although grain output had increased steadily in recent years, groundwater and energy consumption for agriculture didn't have the corresponding increase actually; it was mainly because water-saving irrigation improve water use efficiency. Water productivity (the ratio of yield to the volume of supplied groundwater) is one of the key indicators of water use efficiency. During 2004–2013, the percentage of water-saving irrigation area increased by 12.9%. Correspondingly, water productivity increased from 3.3 kg m^{-3} to 5.2 kg m^{-3}.

Other studies also confirm that water-saving irrigation is one of the most effective ways to reduce water use without loss of grain output (Belder et al., 2004; Zhang et al., 2013a,b,c; Zou et al., 2013). Main measures to water-saving irrigation are irrigation management and irrigation technologies. Water productivity in terms of irrigation water is about 5–35% higher under alternate wetting and drying (a water-saving irrigation practice) than in continuous flooding (Moya et al., 2001). The application of pressurized systems could reduce water consumption by 10%–66%, and water use efficiency is also enhanced without reduction in grain yield (Jackson et al., 2010). Without loss of yield, experimental trials have shown that the water-saving potentials of several high-capacity irrigation technologies exceed 90% (Abdulai et al., 2005).

However, in the NCP, over half of the irrigated area employed traditional irrigation techniques, which caused waste of water and energy resources. This was in marked contrast to the situation in advanced countries in the field of irrigation techniques. In Israel, almost all of irrigation areas are under water-saving irrigation and the efficiency keeps on improving. Moreover, the actual irrigation water use reached up to 1.5 times more than the grain water requirement in the NCP (Wang et al., 2002). The overall water use efficiency of grain production in the NCP has fallen behind the world average, due to poor irrigation management practices and lack of investment in infrastructure (Blanke et al., 2007). This implies that there is a tremendous opportunity for saving groundwater and energy consumption in the NCP by developing water-saving irrigation.

By significantly reducing the amount of water that needs to be pumped, energy consumption and GHG emissions are also reduced in most cases. The application of pressurized systems could reduce energy consumption by 12–44% (Jackson et al., 2010). A study from the USA (Lal, 2004) indicates that the emissions from drip irrigation (216 kg CO^2e) are far less than furrow irrigation (395 kg CO^2e). In 11 surveyed provinces in China, low pressure pipeline irrigation can save 6.48×10^9 kWh yr^{-1} energy and reduce GHG emissions by 6.72 Mt yr^{-1} (Zhang et al., 2013a,b,c). Renewable energy would be an effective way to reduce energy consumption. Solar photovoltaic water pumping system has been widely studied and applied (Chandel et al., 2015). It requires no fuel cost and is environmentally friendly. Most parts of NCP are rich in solar energy according to National Energy Administration. However, if groundwater levels keep decreasing, more photovoltaic water pumping systems are still needed. Therefore, energy-saving technologies will work better in combination with water-saving technologies.

Now water-saving irrigation practices have been one of the China's basic national policies. However, there are some factors restricting the development of water-saving irrigation. Compared to traditional irrigation, water-saving irrigation systems need more funding (Li et al., 2003; Wang, 2010; Yao et al., 2005). There is a higher workload associated with the control and maintenance of equipment (Wang and

Gao, 2001; Wang and Wu, 2006). Overcoming these barriers would require finance, technology and capacity building supports. Therefore, policy makers need to contribute the majority of financial investments to reduce the adverse effects of water scarcity and encourage energy saving. Besides, a reasonable adjustment of water price maybe make water-saving irrigation cost less than traditional irrigation. Subsidy is another way to promote water-saving irrigation.

5. Conclusion

Over-exploitation of groundwater has caused severe groundwater declines in NCP, at a rate of 0.6 m yr^{-1}. This trend becomes faster in recent years. Due to declines in groundwater levels, groundwater pumping for irrigation becomes increasingly energy-intensive and emits more GHGs. Within the last 18 years, energy use rate of unit water pumping increased from 0.5040 kWh m^{-3} to 0.6088 kWh m^{-3}, by nearly 22%. Total GHG emissions have increased from 6.16 to 8.72 Mt CO_2e, by 42%. Hebei suffers the most serious groundwater declines and emits the largest GHG from pumping, accounting for 47% of the total emissions in the NCP.

Energy cost of pumping irrigation is notable (US$ 1.15 billion), because of a large amount of energy consumption. To reduce cost, more electric pumps should be used to replace diesel pumps in this region. In addition, the cost of cutting emissions from pumping irrigation (8.72 Mt CO2e) was US$ 0.087 billion in 2013. In consideration of energy consumption and emission reduction, the total economic cost is US$ 1.25 billion, reaching up to 10.3% of GDP. The increasing cost is a great threat to sustainable development of agriculture.

Water-saving irrigation is an effective way to reduce water and energy consumption without loss of grain output. An average 1% of water-saving irrigation area would increase 0.13 kg m^{-3} water productivity. During 2002–2013, water productivity increased from 3.3 kg m^{-3} to 5.2 kg m^{-3} as the percentage of water-saving irrigated area increased 12.9%. To reduce GHG emissions and pressures on energy and groundwater resources, water-saving irrigation should be greatly promoted in the NCP. However, there are some factors restricting the development of water-saving irrigation in this region. In the future, policy makers need to contribute the majority of financial investments.

Acknowledgments

Great thanks also to Dr. Jianhua Wang, Cangzhou Normal University, for her scientific comments and suggestions. Special thank is also owed to the language editors from Webshop for their efforts in improving the grammar of this paper.

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